

# A Compact Fusion Device based on the Sheared Flow Stabilized Z-Pinch\*

Uri Shumlak for the FuZE Team

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with Zap Energy Inc.

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# Presentation Outline

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- The simplicity and many other advantages of the Z-pinch
- Historical scientific development leading to our sheared flow stabilization approach – SFS Z-pinch
- ARPA-E-funded FuZE, Fusion Z-pinch Experiment, and the development path for the SFS Z-pinch
- Recent alignment of critical factors that make now the right time to advance the SFS Z-pinch as a compact fusion reactor

# Z-pinch configuration has many appealing features

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The Z-pinch has the simplest geometry of any magnetic confinement configuration:

- cylindrical plasma column

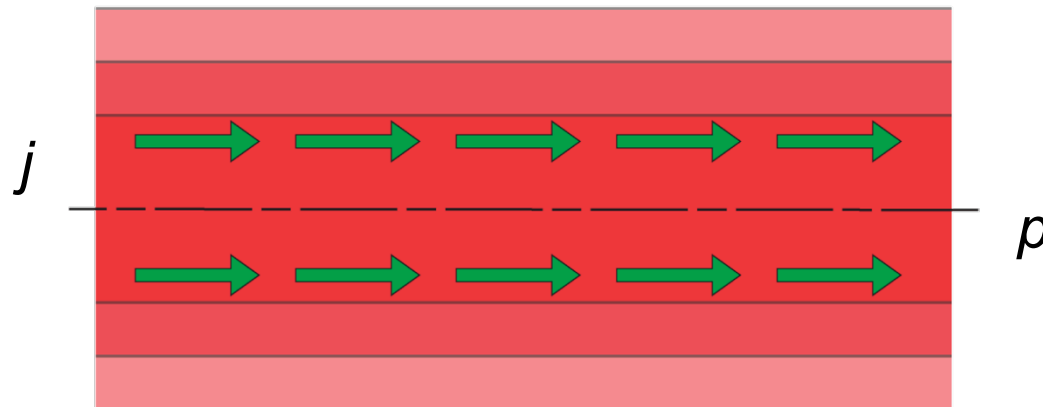


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The Z-pinch has the simplest geometry of any magnetic confinement configuration:

- cylindrical plasma column
- directly driven axial current



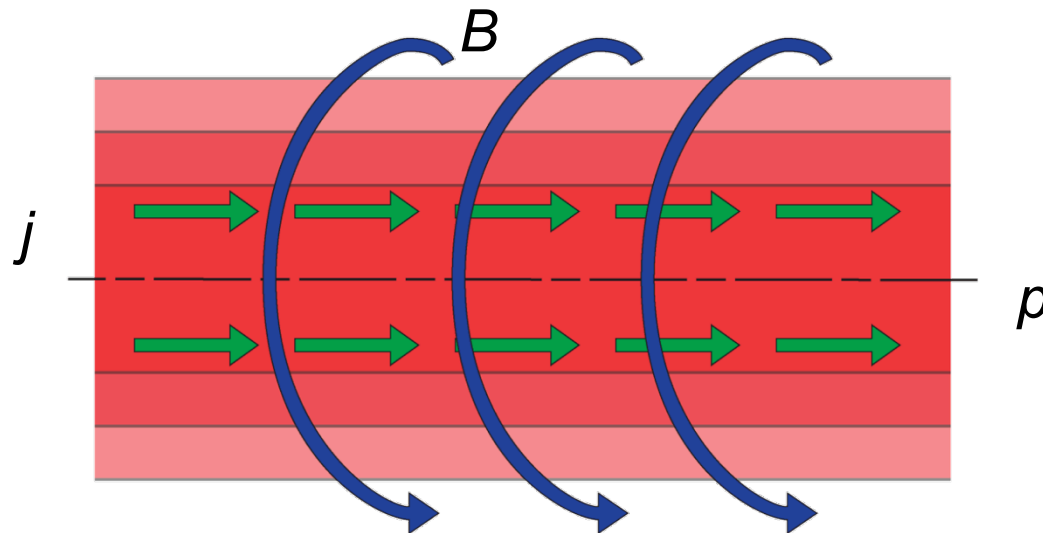


# Z-pinch configuration has many appealing features

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- cylindrical plasma column
- directly driven axial current
- self-generated magnetic field compresses the plasma

$$\frac{dp}{dr} = -\frac{B}{\mu_0 r} \frac{d(rB)}{dr}$$

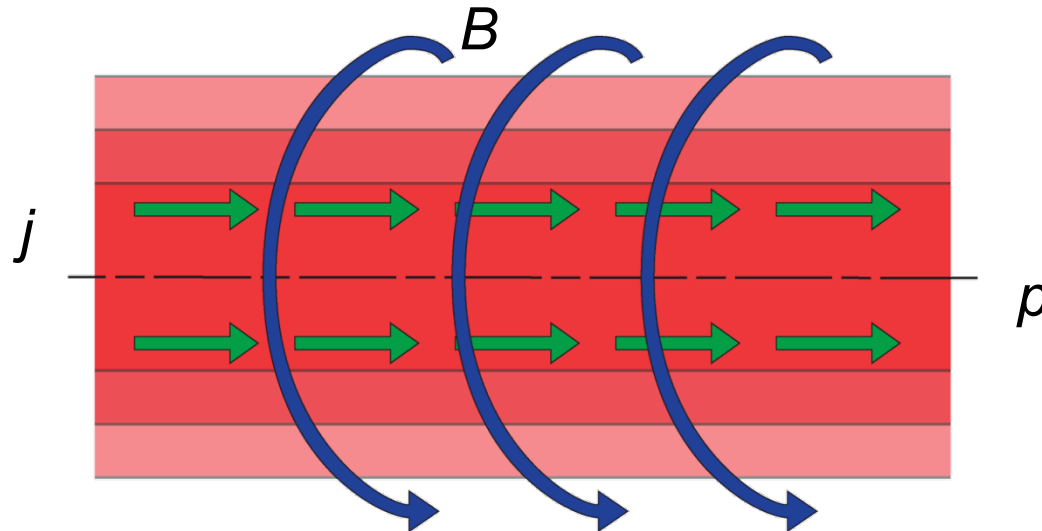


# Z-pinch configuration has many appealing features

The Z-pinch has the simplest geometry of any magnetic confinement configuration:

- cylindrical plasma column
- directly driven axial current
- self-generated magnetic field compresses the plasma
- perfect utilization of the magnetic field for compression,  $\beta=100\%$
- no magnetic field coils: greatly reducing cost, size, and complexity
- increasing the current generates higher plasma parameters, increased fusion production, and smaller plasma radius

$$\frac{dp}{dr} = -\frac{B}{\mu_0 r} \frac{d(rB)}{dr}$$



# Z-pinch research predates nuclear fusion understanding

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1790: Earliest “Z-pinch” research by Martinus van Marum

1905: Observation of crushed lightning rod by Pollock & Barracclough

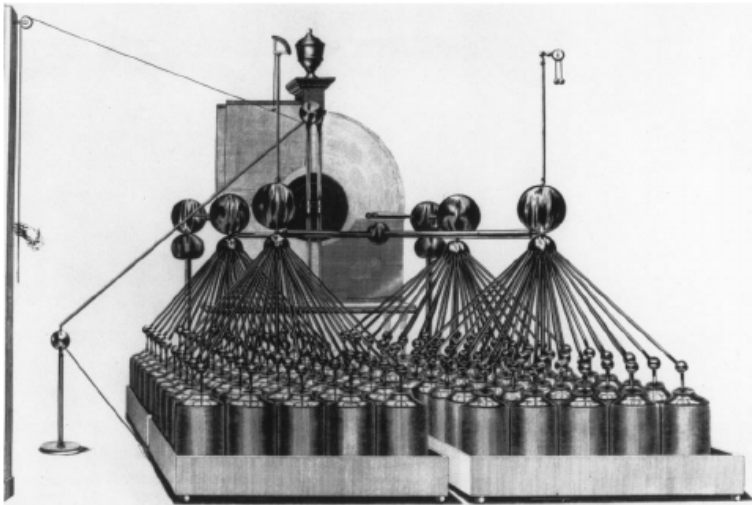
1907: “Pinch phenomenon” in liquid conductor by Northrup

1934: Theoretical model of plasma Z-pinch by Bennett

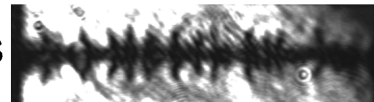
1950: Z-pinch was Project Sherwood Jim Tuck’s preferred approach to achieve controlled fusion

1957: Theory and experiments demonstrated virulent instabilities,  $m = 0, 1$

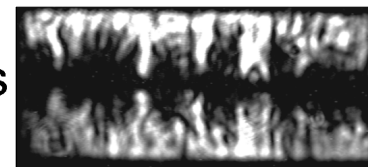
1998: Performance of Z-pinchs using frozen deuterium fibers was severely limited by these instabilities



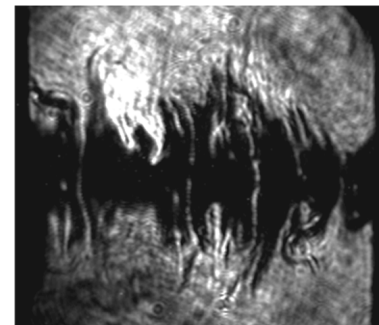
27 ns



55 ns



117 ns

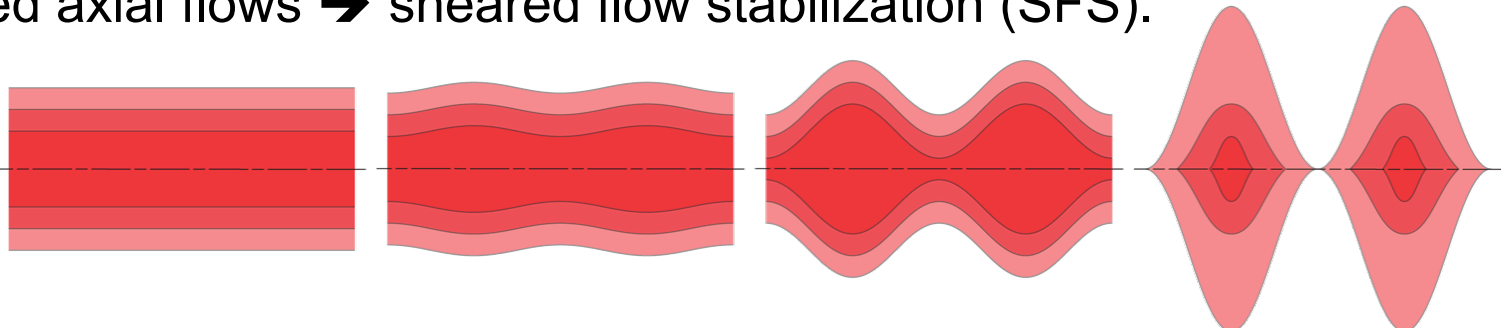


# Key Innovation: sheared flows can stabilize the Z-pinch

Prior theoretical and experimental research focused on static Z-pinch plasmas, and demonstrated that  $m = 0$  and  $m = 1$  instabilities persist.

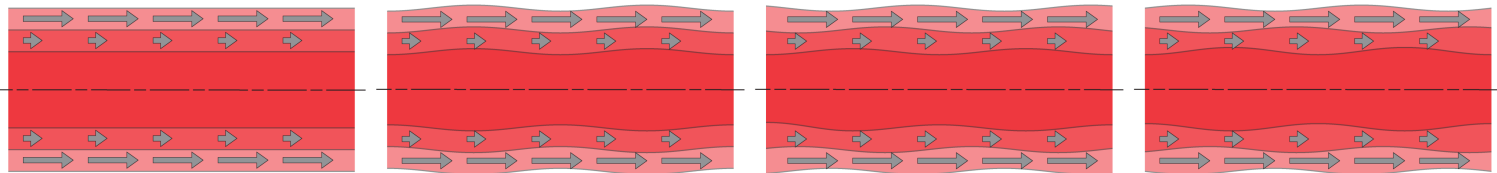
1995: Theoretically demonstrated that a Z-pinch could be stabilized with low-speed axial flows → sheared flow stabilization (SFS).

No flow



Sheared flow

$$\frac{dv_z}{dr} \neq 0$$



VOLUME 75, NUMBER 18

PHYSICAL REVIEW LETTERS

30 OCTOBER 1995

## Sheared Flow Stabilization of the $m = 1$ Kink Mode in Z Pinches

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*High Energy Plasma Division, Phillips Laboratory, Kirtland Air Force Base, Kirtland, New Mexico 87117-5776*

C. W. Hartman

*Lawrence Livermore National Laboratory, Livermore, California 94550*

(Received 6 April 1995)

The effect of a sheared axial flow on the  $m = 1$  kink instability in Z pinches is studied numerically by reducing the linearized magnetohydrodynamic equations to a one-dimensional displacement equation. An equilibrium is used that is made marginally stable against the  $m = 0$  sausage mode by tailoring its pressure profile. The principal result reveals that a sheared axial flow stabilizes the kink mode when the shear exceeds a threshold that is dependent on the location of the conducting wall. For the equilibria studied here the maximum threshold shear ( $v_z'/kV_A^0$ ) was about 0.1.

# Scientific advancement of sheared flow stabilization

1998 – 2014: DOE-funded experimental project at the University of Washington to conduct a scientific investigation of sheared flow stabilization in the Z-pinch → ZaP & ZaP-HD projects

- produced long-lived, stable Z-pinch plasmas
- demonstrated robustness of sheared flow stabilization: stable for 1000's times longer than static pinch
- investigated limits of stability
- developed understanding of plasma behavior and how to control it
- achieved pinch currents of 50 kA

VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

## Evidence of Stabilization in the Z-Pinch

U. Shumlak,<sup>1</sup> R. P. Golingo, and B. A. Nelson  
*University of Washington, Aerospace and Energetics Research Program, Seattle, Washington 98195-2250*

D. J. Den Hartog\*  
*Sterling Scientific, Inc., Madison, Wisconsin*  
(Received 11 June 2001; published 29 October 2001)

Theoretical studies have predicted that the Z-pinch can be stabilized with a sufficiently sheared axial

PHYSICS OF PLASMAS

VOLUME 10, NUMBER 5

MAY 2003

## Sheared flow stabilization experiments in the ZaP flow Z pinch<sup>ab</sup>

U. Shumlak,<sup>1</sup> B. A. Nelson, R. P. Golingo, S. L. Jackson, and E. A. Crawford  
*University of Washington, Aerospace and Energetics Research Program, Seattle, Washington 98195-2250*

D. J. Den Hartog  
*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706*  
(Received 7 November 2002; accepted 9 January 2003)

The stabilizing effect of a sheared axial flow on the  $m=1$  kink instability in Z pinches has been studied numerically with a linearized ideal magnetohydrodynamic model to reveal that a sheared

[HTML, ABSTRACT + LINKS](#)

PHYSICS OF PLASMAS 12, 062505 (2005)

## Formation of a sheared flow Z pinch

R. P. Golingo,<sup>1</sup> U. Shumlak, and B. A. Nelson

*Aerospace and Energetics Research Program, University of Washington, Seattle, Washington 98195-2250*

(Received 4 January 2005; accepted 15 April 2005; published online 27 May 2005)

The ZaP Flow Z-Pinch project is experimentally studying the effect of sheared flows on Z-pinch stability. It has been shown theoretically that when  $dV/dx$  exceeds  $0.14V_0$  the kink ( $m=1$ ) mode is stabilized. [U. Shumlak and C. W. Hartman, Phys. Rev. Lett. 75, 3285 (1995)] Z pinches with an embedded axial flow are formed in ZaP with a coaxial accelerator coupled with a 1 m assembly

IOP Publishing and INTERNATIONAL ATOMIC ENERGY AGENCY

Nucl. Fusion 49 (2009) 075039 (9pp)

NUCLEAR FUSION

doi:10.1088/0029-5558/49/7/075039

## Equilibrium, flow shear and stability measurements in the Z-pinch

PHYSICS OF PLASMAS 24, 055702 (2017)



## Increasing plasma parameters using sheared flow stabilization of a Z-pinch

U. Shumlak,<sup>1,10</sup> B. A. Nelson, E. L. Clavau, E. G. Forbes, R. P. Golingo, M. C. Hughes, R. J. Oberst, M. P. Ross, and T. R. Weber  
*Aerospace and Energetics Research Program, University of Washington, Seattle, Washington 98195-2400, USA*

(Received 9 December 2016; accepted 30 January 2017; published online 28 February 2017)

The ZaP and ZaP-HD Flow Z-pinch experiments at the University of Washington have successfully demonstrated that sheared plasma flows can be used as a stabilization mechanism over a range of parameters that has not previously been accessible to long-lived Z-pinch configurations. The stabilization is effective even when the plasma column is compressed to small radii, producing predicted increases in magnetic field and electron temperature. The flow shear value, extent, and duration are shown to be consistent with theoretical models of the plasma viscosity, which places a design constraint on the maximum axial length of a sheared flow stabilized Z-pinch. Measurements of the magnetic field topology indicate simultaneous azimuthal symmetry and axial uniformity along the entire 100 cm length of the Z-pinch plasma. Separate control of plasma acceleration and compression has increased the accessible plasma parameters and has generated stable plasmas with radii of 0.3 cm, as measured with a high resolution digital holographic interferometer. Compressing the plasma with higher pinch currents has produced high magnetic fields (8.5 T) and electron temperatures (1 keV) with an electron density of  $2 \times 10^{21} \text{ cm}^{-3}$ , while maintaining plasma stability for many Alfvén times (approximately 50  $\mu\text{s}$ ). The results suggest that sheared flow stabilization can be applied to extend Z-pinch plasma parameters to high energy densities. Published by IOP Publishing.

<http://dx.doi.org/10.1063/1.4977468>

## 1. INTRODUCTION

Magnetic compression and confinement of plasma in a Z-pinch configuration date back to the earliest investigations

conductivity. Shear flow stabilization, generated by differential  $E \times B$  drift, has been used to improve tokamak confinement and to explain observed H-mode transitions.<sup>1,2</sup> A general review of sheared flow stabilization and suppression of magnetic

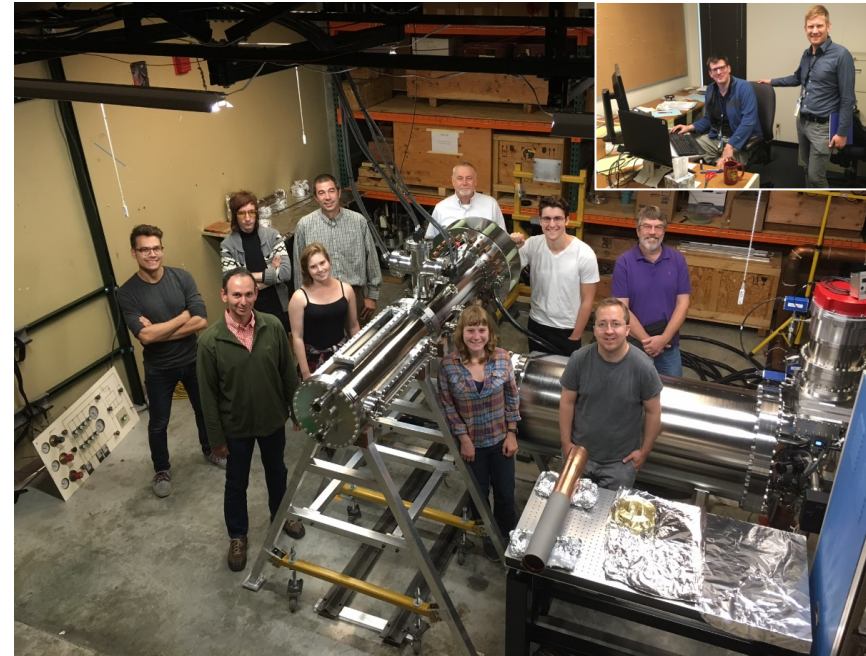
\*Electronic mail

# FuZE Project is advancing the SFS Z-pinch for fusion

Sheared flows provide complete stability at moderate plasma currents.

- Will the stabilizing effect continue as current is increased?

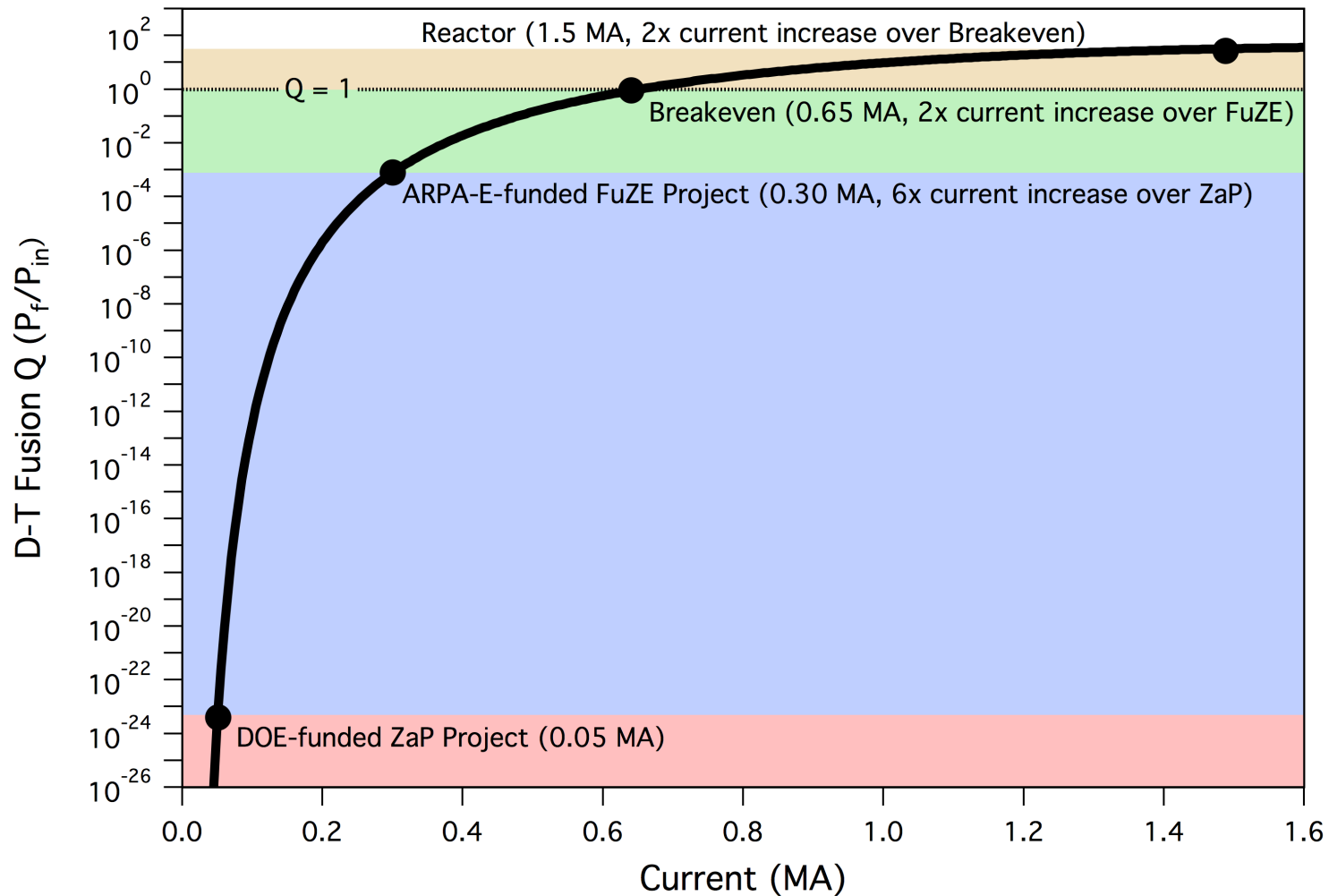
ARPA-E ALPHA Program funded the UW/LLNL FuZE Project at  $\approx 10\times$  previous levels to explore the potential of the SFS Z-pinch as a compact fusion device.



- incorporates LLNL's scientific expertise and hardware
- builds on the success of our previous SFS Z-pinch projects
- to advance the SFS Z-pinch fusion concept to the next step along the development path.

# Development path for the SFS Z-pinch fusion core

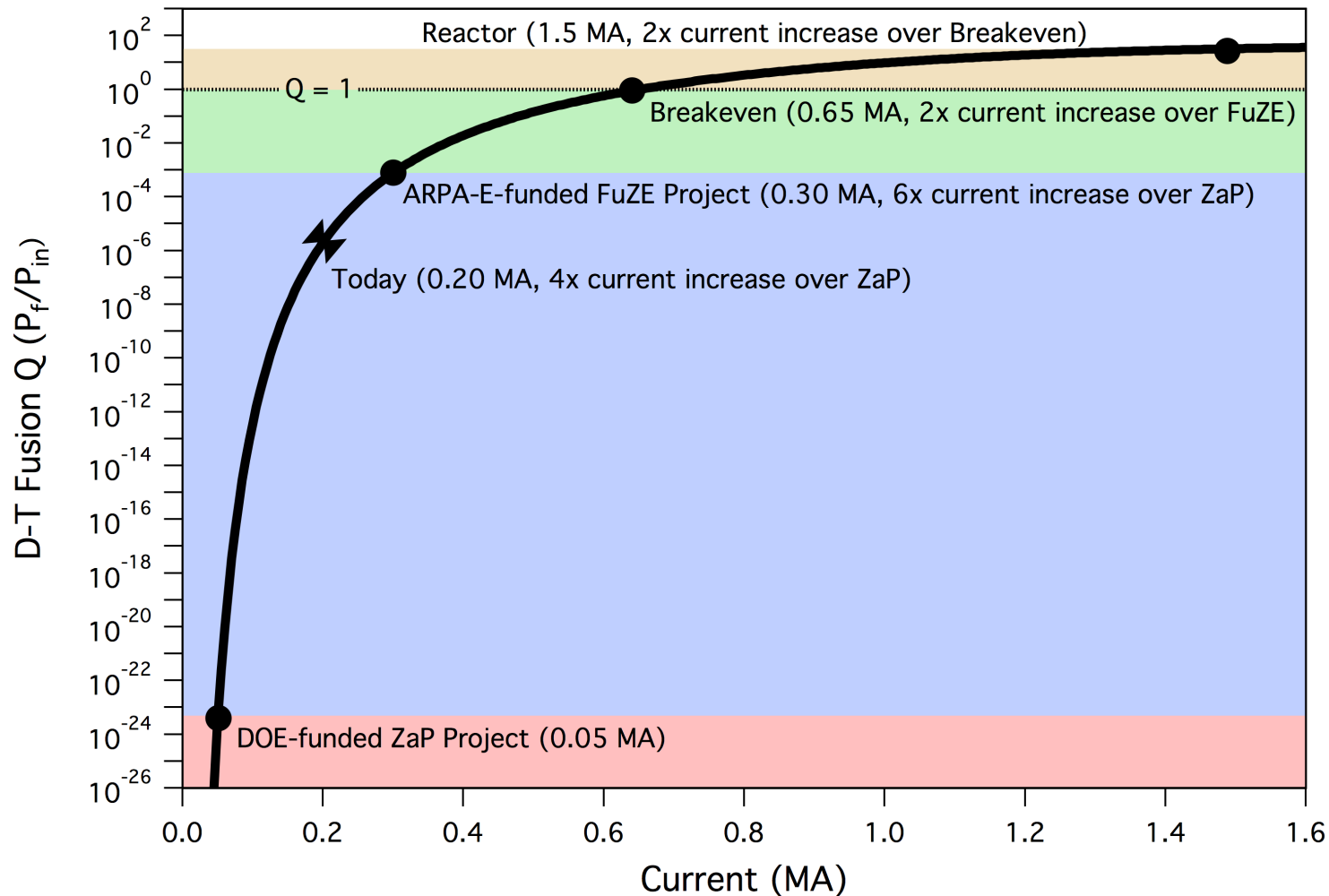
Increases in plasma current mark the key steps along the development path for the SFS Z-pinch fusion core.





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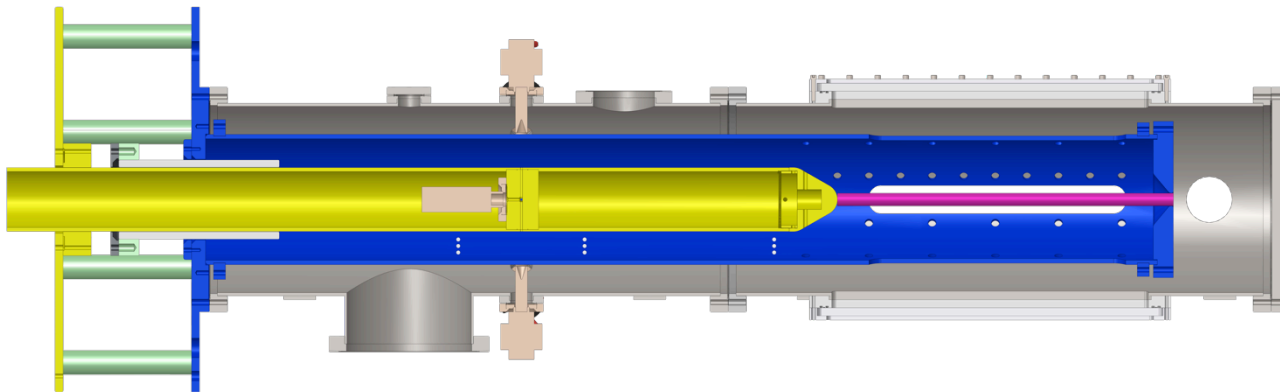


# Now is the right time for SFS Z-pinch fusion

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Four critical factors have converged:

1. ARPA-E funding has enabled us to push the SFS Z-pinch concept much further than previously possible, e.g. 6x current increase.
2. Computational power and simulation tools allow detailed modeling of sheared flow stabilization that support the experimental effort.
3. Encouraging experimental and computational results indicate sheared flow stabilization is robust even at higher currents. (Visit our technical poster for details.)
4. Growing recognition that a carbon-free power source is desperately needed and that current mainline fusion approaches are too costly and advancing too slowly to contribute to the solution.



# ZAP ENERGY INC

## RAISING SERIES A FUNDING



- ◆ ZAP ENERGY INC was incorporated in May 2017 as a spin-out from the UW and LLNL, contact Benj Conway, [reachout@zapenergyinc.com](mailto:reachout@zapenergyinc.com)
- ◆ ZAP ENERGY is raising Series A funding to demonstrate breakeven
- ◆ Targeting a compact, commercial fusion application
- ◆ Building on significant breakthroughs in fusion technology developed by UW and LLNL team since 2015
- ◆ Signed a proprietary intellectual property licensing agreement in June 2017
- ◆ ARPA-E funded until August 2018 after which ZAP ENERGY team to physically spin-out of UW onto new premises
- ◆ Team has over 90 years combined experience in fusion research
- ◆ Substantial advantages by removing the need for costly and complicated magnetic coils
- ◆ FuZE project equipment provided by UW to ZAP ENERGY on loan
- ◆ Substantially reduced risk through validation of technology with historical DOE grant funding and existing ARPA-E award, which provides funding through August 2018



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